On-Board Single-Phase and Three-Phase Integrated Battery Charger for an Electric Vehicle

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Abstract: Vehicle (PEV). Charger is a very essential part of an Electric Vehicle (EV), and used to charge the battery packs. The charging rate of battery mainly depends upon the capacity of the charger, higher rating charger, charged the battery much faster rate compared to low capacity charger. Proposed work used power electronic components for charging and propulsion of EV. Power electronic components like DC-DC converter, and inverter are used for propulsion of EV. Further, these components also used to charge the battery. It means power electronic components are integrated for both charging and propulsion mode. Integrated charger contains components for propulsion are also used for charging, like induction machine stator winding used as inductive filter, inverter as rectifier, DC-DC converter in BUCK mode to charge the battery. In this project, CUK converter has been used instead of ordinary BUCK-BOOST DC-DC converter. During charging mode CUK converter acted as BUCK converter, and during discharging CUK converter acted as BOOST converter to meet the required voltage level. CUK converter improves efficiency because of low switching losses. Due to a smaller number of components, overall cost of charger is reduced. Further, due to integrated charger volume, cost, and size of electric vehicle is decreased. Integrated charger charged the battery at faster rate, and it can be plugged to both single-phase AC source or to the three-phase AC source depending upon the availability. In this work, charging of battery carried out using from both single-phase and three-phase supply. Charging and discharging results of battery are obtained using MATLAB simulation. Hardware implementation is also carried out considering vehicle to grid (V2G) mode.

Keywords: **Electric Vehicle, CUK converter, Integrated charger, Battery storage system.**

I. INTRODUCTION

The Emission of Greenhouse Gas (GHG) is the unwanted byproduct which is associated with burning of fossil fuel. Global warming reaches to dangerous level due to worldwide pollution. Immediate action needed to reduce the pollution Level of the world to prevent the world from the disaster.

According to international energy, by 2050 GHG will be doubled if no such preventive action will be taken [1].

Due to the increasing pollution level of the environment, the government is more concerned about reducing the pollution level of the country. There are many sources of air pollution and one major source is automobile sector. So the government applying many schemes to reduce pollution from automobile sector, and one of them is to use an electric vehicle [2]. To charge an electric vehicle power supply is required, which is ultimately obtained after burning the fossil fuel. To electrifying only transport sector is not the solution to reduce the global warming. In addition of electrifying the transport sector, use of renewable energy (solar, wind type of energy) sources to charge the battery packs should be enhanced, then only transport sector can contribute in pollutionreduction.

Air pollution is very critical for health. Some of the Indian cities are most polluted compared to other cities of world. As per the study carried out in 2016 shows that at least 140 million Indian people are breathing 10 times more hazardous air compared to WHO safe limit. Air pollution study shows that the 51% of pollution is caused by the industries, 27% by vehicles, 17% by crop burning and 5% by fire crackers. Two million deaths per year in India occurred due to air pollution.

II. COMPONENTS

1) Battery

In a standard electric vehicle, the battery is the only component to store the energy and to give the power to the drive of electric vehicle and hybrid electric vehicle [3]. These batteries are usually rechargeable type or called as a secondary type of batteries.

A battery consists of cells that are connected in a particular fashion and converts chemical energy into electrical energy as DC electricity [4]. This DC electricity is used to give the power to the electric vehicle drive via an inverter. In case of a secondary battery, the reverse reaction is also possible so that battery returned into a charged state.

Lead-Acid battery:

The lead-acid batteries are the most used and most affordable type of batteries those are used in an Electric-vehicle. There are two types of batteries such as starter batteries and deep-cycle batteries. Starter batteries are used to start the engine (shorter duty) and deep-cycle batteries for continuous supply (longer duty). No lead-acid battery can discharge below 50% to avoid battery life decay. Further, lead-acid batteries end up being with significant (25-50%) of vehicle mass and they have very less specific energy as compare to other type of batteries. The efficiency is about 70-75% but decreases at lower temperature up to 40%.

2) INTEGRATED CHARGERS

Integrated charging technique is very interesting topology. Using of power electronic components during both in

propulsion and charging mode is known as integrated type of technique.
This technique can be implemented practically because vehicle is in standstill during charging. So, we can use power electronic components during charging which was used during propulsion mode.

Therefore, supply is fed from three phase motor, where stator winding work as an inductive filter. Inverter behaves as rectifier and DC/DC converter act as BUCK converter. So basically, charging mode is totally reverse operation when compare with propulsion mode.

The use of an integrated charger can save, cost, volume, and weight of an electricvehicle.

One biggest advantage of integrated charger is, it can charge the electric vehicle at very faster rate without using external component and without taking electric vehicle to public charging station.

Integrated charger can be developed in different manner

Using of only DC/DC converter for both charging and propulsion mode.

Using of inverter and DC/DC converter for both charging and propulsion mode.

Using of every component, i.e. motor, inverter, DC/DC converter for bothcharging and propulsion mode.

Using of only DC-DC converter during charging mode:

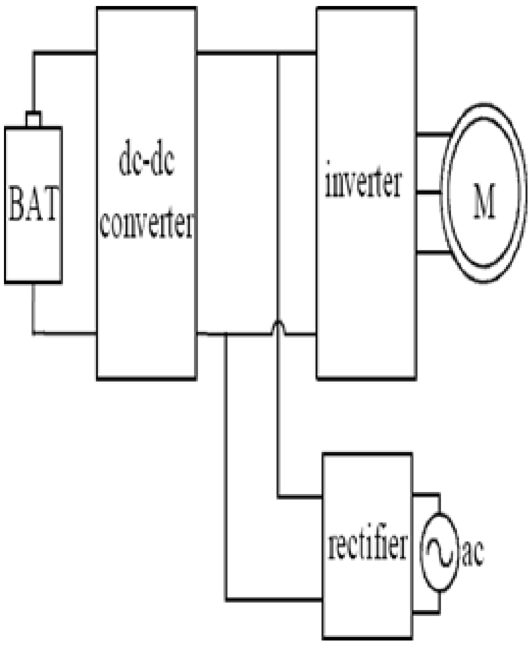


Fig 2.1. Block diagram of integrating DC-DC converter

From this block diagram shown in figure 301, it can be seen that the DC/DC converter used for both charging and propulsion mode. It is the most obvious part of electric vehicle for integration in the charging process.
In propulsion mode DC/DC converter converts low level voltage to a suitable voltage to fed the inverter which is converted from DC supply to AC supply and further fed to motor to drive the electric vehicle. In this configuration DC/DC converter is acted as BOOST converter.
In charging mode, single phase AC supply is fed from the grid and converted into DC supply which is fed to integrated DC/DC converter. It converts high voltage level to a suitable voltage to feed to battery packs for charging. In this type of configuration DC/DC converter is acted as BUCK converter.

The biggest disadvantage of this type of integration is that it integrates only DC/DC converter. Thus, external rectifier is required which further increases weight, cost, volume of an electric vehicle.
Another disadvantage of this topology is that it doesn't charge the electric vehicle at very faster rate as this topology didn't allow use of high rating rectifier due to weight, cost, and volume of an electric vehicle.
In this work, DC/DC converter is implemented as CUCK converter instead of BUCK/Boost converter. The idea of implementation of CUK converter is to reduce the switching losses and reduce the ripples of current which enters into the battery during charging.
By using CUK converter instead of BUCK/BOOST converter, the number of components got reduced so overall switching losses decreases and efficiency increases.

3) CUK Converter:

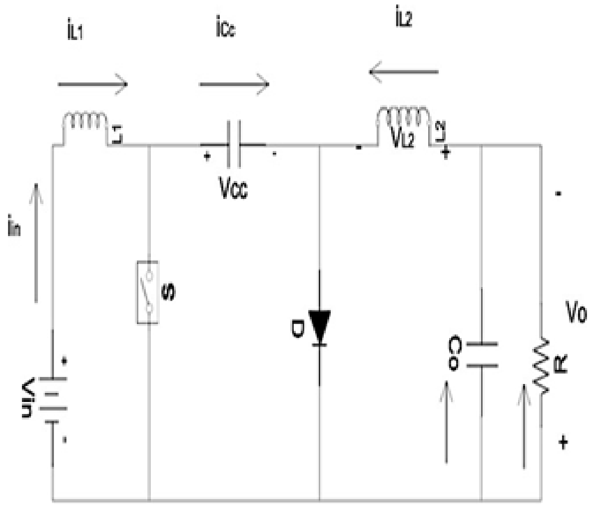


Fig 2.2. Circuit diagram of CUK converter

Working and advantages are already explained in the theory chapter. In this chapter,CUK design parameters and battery charging is discussed..

Designing of CUK :

Inductor design: L selected for current ripple to be about 10-20% of itsmaximum average current.

L_1	L_2
$L_1 = \frac{Vo(1-D)Ts}{\Delta IL_1}$	$L_2 = \frac{Vo(1-D)Ts}{\Delta IL_2}$
$IL_1, peak = Iin, max + \frac{\Delta IL_1}{2}$	$IL_2, peak = Io, max + \frac{\Delta IL_2}{2}$
$DCbias: Iin, max$	$DCbias: Io, max$
$IL_1, rms = \sqrt{Iin^2}, max + \frac{\Delta IL_1{}^2}{12}$	$IL_2, rms = \sqrt{Io^2}, max + \frac{\Delta IL_2{}^2}{12}$

Two inductors can be coupled therefore wound on the same core which can reduce the weight and volume of inductance and cost as well and if designedproperly then ripple also reduces.

Designed parameters value of CUK converter:

CUK converter compare with BUCK/BOOST converter:

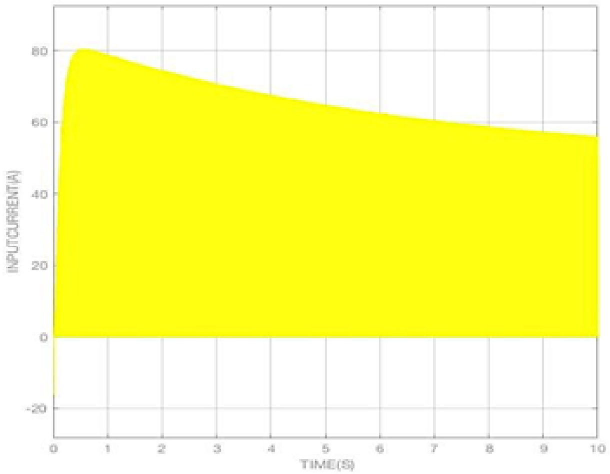


Fig 2.3. Simulation result of BUCK converter

This is the simulation result when I used BUCK converter during charging and this is the input current which fed to BUCK converter. It is observed from the result, current ripples are very much which can damage the equipment's.

Battery parameters

Nominal voltage: 200VCapacity = 10AH
SOC (%) = 20KWHR = 2

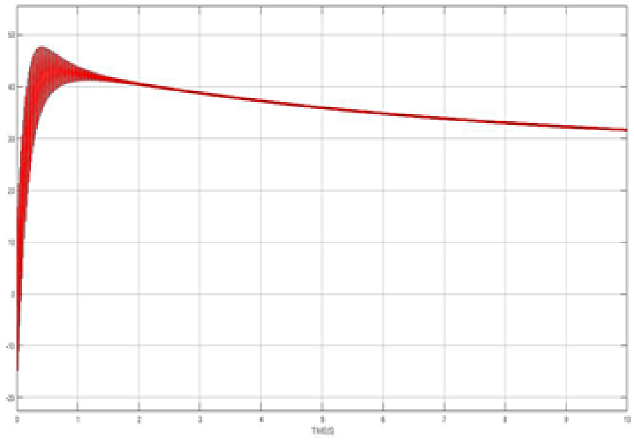


Fig 2.4. Simulation result of CUK converter

This is the simulation result of CUK converter instead of BUCK converter during charging. By designing the suitable values of the parameters, input current which is fed to CUK converter has less ripples compared to BUCK converter.

For short time ripple is more and then constant current is fed without any ripple which protects the power electronic equipment's.

For CUK converter

Input voltage, rms value=
230V ,50HZDc coupling
voltage =350 V
Duty ratio = 40%Cc = 150µf
Co = 50µf
L_1, L_2 = 30mHVo = 233V

This CUK converter charged the battery depending upon the rating of battery and the supply used.

Designed value of Battery:

III. CONTROLLER

Controller is used to control the pulse width of inverter [5] by using the technique of Clarke's and Park's transformation, phase locked loop (PLL). During discharging of battery, battery DC power is converted to ac power by inverter and inverter pulse widthis controlled by controller.

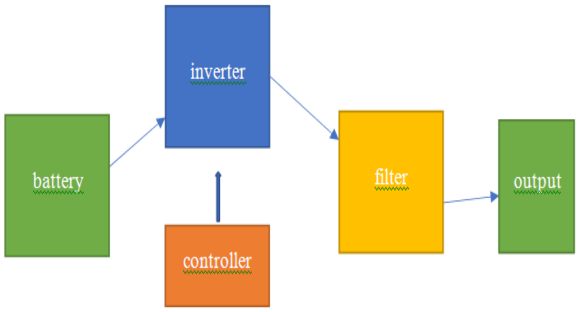


Fig 3.1 Block diagram during discharging of battery

From the block diagram, it can be seen that battery is discharging through an inverter, which convert DC supply into AC supply. Controller controlled the pulse width of an inverter depends upon the requiring output voltage. Output from the inverter contains harmonics which will filter out by the filter (stator winding of an induction machine). The filtered output is free from harmonics.[6]

Simulation result of decoupling:

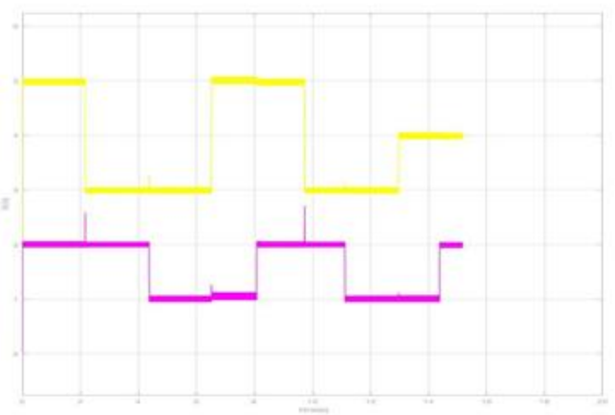


Fig 3.2 Simulation result of decoupling

It represent between $I_d(direct\ axis\ current)$, $I_q(quadrature\ axis\ current)$ and Time.

The result shows I_d, I_q are decoupled to each other, so active and reactive poweris also decoupled to each other.

It means the variation of I_d does not affect I_q and variation in I_q does not affect the I_d.

Decoupling makes controlling very easy as they can control individually.

IV **Modelling of an integrated charger**

1) Integration of existing component with single-phase source:

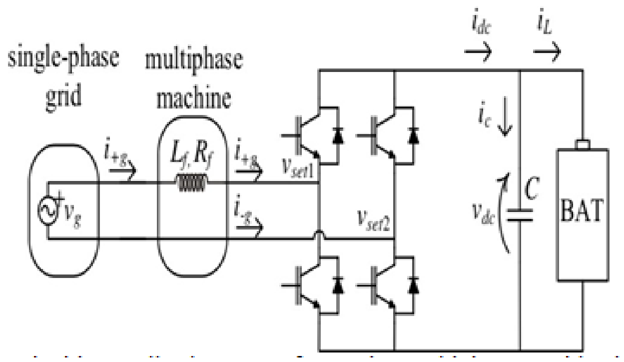


Fig 3.3 Integrated charger with single-phase

This figure represents integrated charger with single-phase source [7]. In this configuration single-phase AC source is applied from the grid. Grid supply will convert into DC via single phase full bridge rectifier. Outputvoltage ripple will be removed By choosing appropriate value of DC-link capacitor. During charging or say Grid to Vehicle (G2V) mode, converter will act as single-phase full bridge rectifier. During discharging or say (V2G) mode, converter will act as multilevel or two level inverter depends upon our requirement.

A CUK converter will operate in both mode, BUCK converter during charging and BOOST converter during discharging to meet the required voltage level.

Single-phase integrated charger is very attractive due to the availability of single-phase AC source and their fast charging capability. By simple hardware setup we can convert multilevel inverter into single-phaseAC bridge rectifier.

2) Integration of existing component with Three-phase source:

In this type of configuration all components, i.e. power electronic and electric drive, used for both charging and propulsion mode [8].

Power flow during traction is from battery to induction motor via Bidirectional DC/DC converter and Bidirectional DC/AC converter.

During propulsion or traction mode bidirectional DC/DC converter act as a BOOST converter to meet the desired voltage level which is fed to inverter.

Bidirectional DC/AC (Inverter) convert from DC to AC supply which is fed to induction motor.

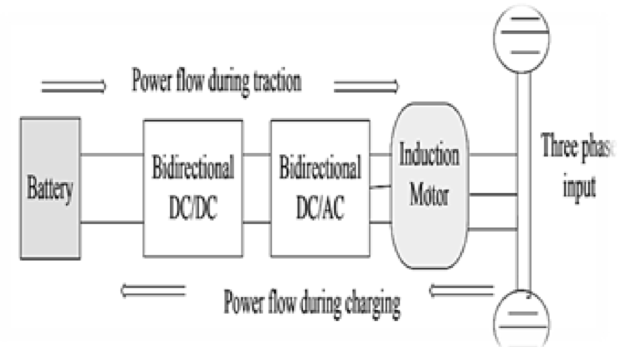
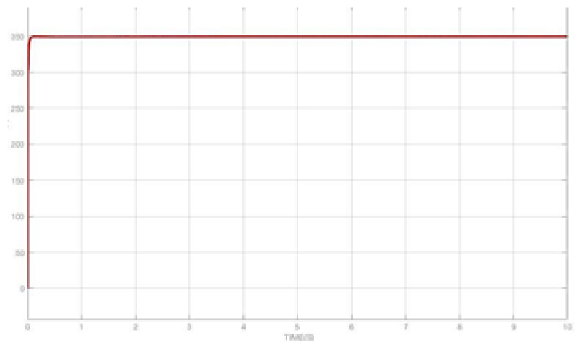


Fig 3.4. Block diagram of integration of IM and inverter

An induction motor can be multiphase (more than three phase) machine, i.e. asymmetrical nine-phase, an asymmetrical, and a symmetrical six-phase machine. In all machine both charging and vehicle to grid(V2G) is possible. So, during charging/V2G mode induction motor stator winding will act as an inductive filter which will reduce the current ripple and used for unity power factor correction.

The biggest disadvantage of not using multiphase machine is, during charging rotating magnetic field will generated which will produce torque and machine will start rotating which is unnecessary during charging. It will increase losses.
Multiphase machine is not having this kind of problem because in multiphase machine existing torque plane transfer to nonexistent torque plane which will not produce that much torque which can drive the induction machine.

Single phase charging is very slow charging process, nevertheless electric vehicle installed with fast three-phase integrated charger. It can also use as single-phase charging technique because of widely spread of single-phasesource.



3) Model of an integrated charger with three-phasesource:

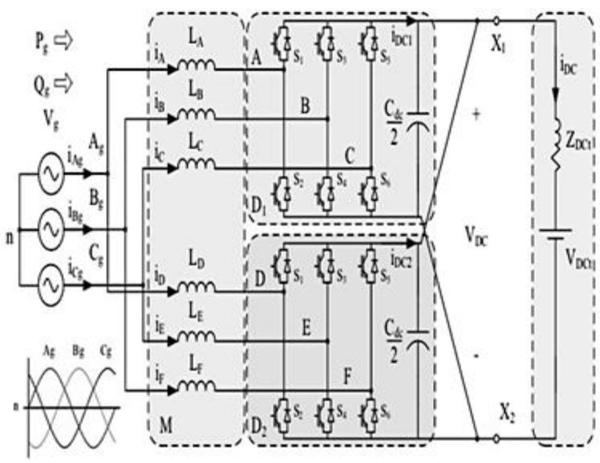
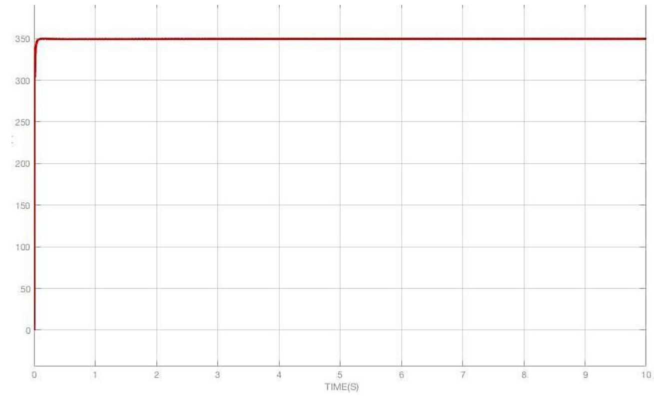


Fig. 3.5. Model of an integrated charger

This figure represents the model of integrated charger with three-phase source [9].
Three phase supply is taken from the grid.
Three phase induction machine is reconfigured in six phase multiphase machineto cancel out the torque.

Stator winding of an induction machine simply used as an inductive filter to filter out the current harmonics which is taken from the grid.

Two six pulse converter are connected to convert from the AC



to DC. Output of rectifier is capacitor which act as a DC-link capacitor to connect one part of the circuit to other part of the circuit.
This DC output voltage is fed to the CUK converter, which is used specially in this project. This CUK converter will step down the dc voltage to suitable level of battery which is connected to output of the converter.

Battery will charge at constant voltage and at constant current. Its SOC (state of charge) will charge from its normal value to full depending upon the designed parameters.

During discharging of battery reverse will happen and ultimately the power output from an inverter can be fed to an induction machine to drive it or to the grid to fed back to supply, this technique also called as vehicle to grid (V2G) technique.

IV. Simulation Results

Effect of source inductance:

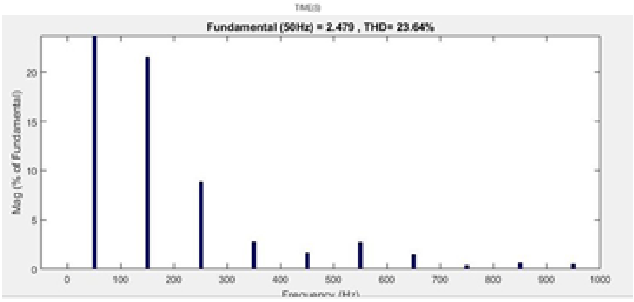


Fig 4.1 THD without source inductance

It can be seen from the results that the total harmonic distortion is 45.54%without source inductance.

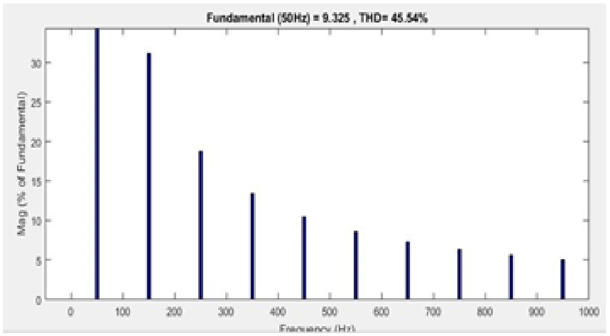
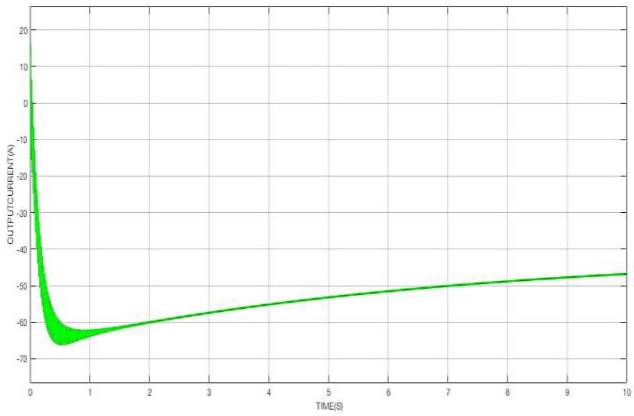


Fig 4.2 THD with source inductance

It can be seen from the results that the total harmonic distortion is 45.54% without source inductance. In second result, total harmonic distortion reduced to 23.64% due to source inductance.



Results due to integration of existing component with single-phasesource:

DC-link output voltage of rectifier:

Fig5.3. Simulation result of rectifier

The output from rectifier connected to single phase AC source is shown in figure 5.3. Result showed that DC-link voltage is 350 volts without any ripple. It is only because of choosing suitable value of DC-link capacitor.

Input current fed to the CUK converter:

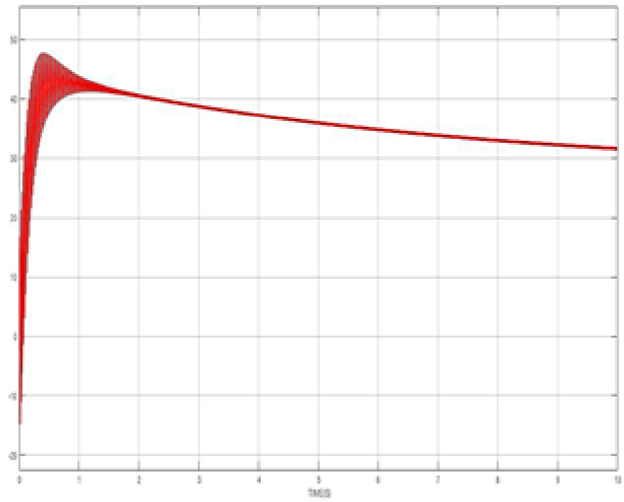


Fig4.4. Simulation result of input current fed to CUK converter

The current waveform which is fed to CUK converter is shown in figure 5.4. It is observed from the result that at starting there are some ripples because of inductance as inductance doesn't allow sudden changes in current. After some time ripples reduced to zero and current remains constant. It happened by choosing the appropriate value of input side inductance in CUK converter.

Output side current of CUK converter

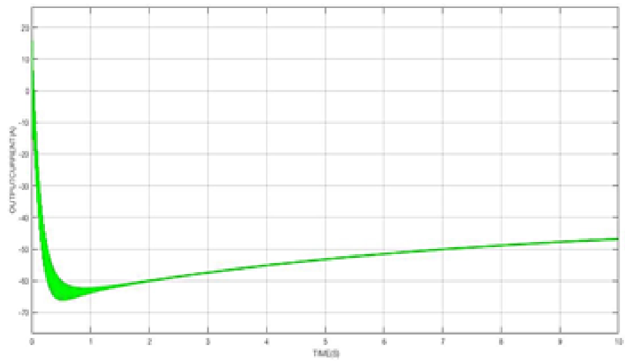


Fig 4.5. Simulation result of output current from CUK converter

Output current waveform of CUK converter is given in figure 5.5 . It can be seen from the result that there are some ripples at starting because of inductance as inductance doesn't allow sudden changes in current. Choosing the appropriate value of output side inductance in CUK converter, ripples reduced to zero and current remains constant. Input side and output side inductance values chosen is approximately equal for easy design.

Output current is having negative value because CUK converter is connected tothe battery.

This is also called the input current of battery as it is supplied by the single- phase AC source.

Battery charging result:

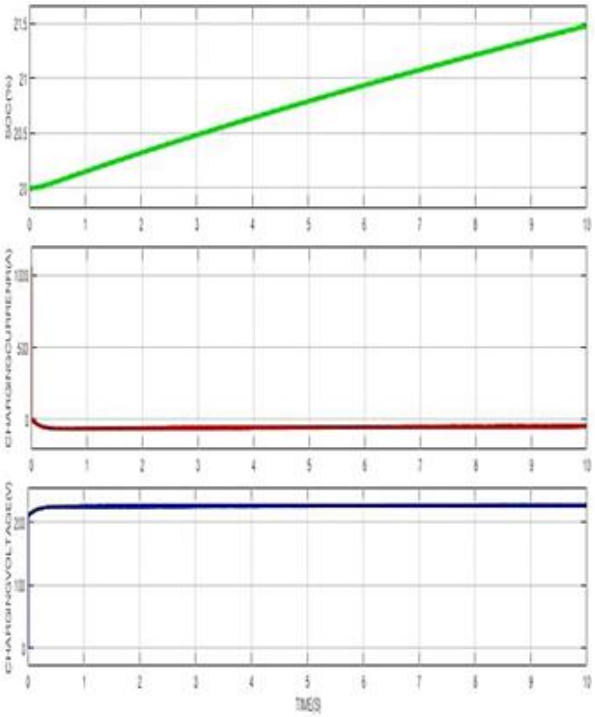


Fig 4.6. Simulation result of battery charging

Simulation results for battery are shown in figure 5.6.

State of charge (SOC) V_S time graph is shown at the top of figure 5.6. It represents the time required by battery for charging from its normal SOC. From the figure, it is observed that the battery charging from 20% to 21.5% required 10 seconds.

Charging current (A) V_S time graph is shown in the middle of figure 5.6 this graph represents, the charging current of battery. The negative value of current shows that the battery is drawing current from the supply at constant rate.

Charging voltage V_S time graph is shown at the bottom of figure 5.6. This graph represents the charging voltage of the battery. Here battery is charging from constant voltage i.e. 230 volts. This voltage also represents the output voltage of CUK converter. Value of voltage depends upon the designed parameters of CUK converter.

Results due to integration of existing component withthree-phase source:

Three phase input voltage:

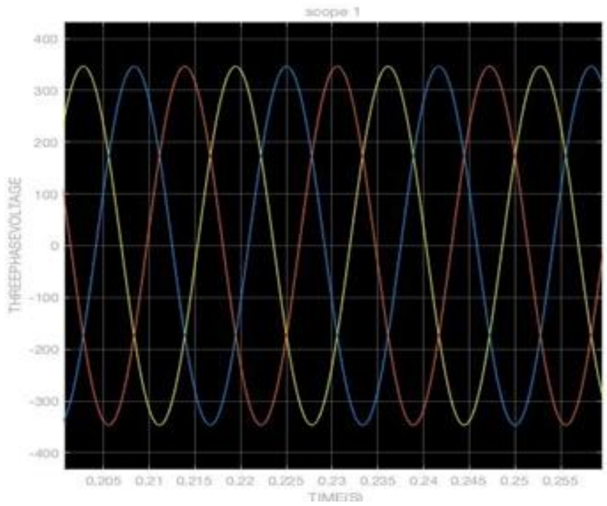


Fig4.7. Simulation result of three-phase input voltage Vs time

The figure 5.7 shows the simulation results of three-phase input voltage supplied fromthe grid Vs time. R, Y, B is taken as the three-phase sequence. R, Y, Bare displaced by 120degree to each other, and having amplitude 350 volts**.**

DC-link output voltage from twelve pulse converter:

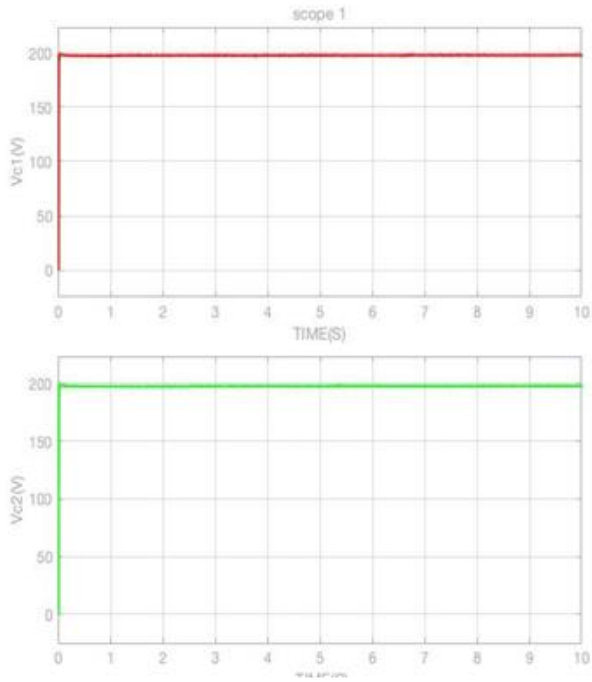


Fig4.8.Simulation result of 12 pulse converter output

Simulation results of 12 pulse converter output are shown in figure 5.8. The graphs shown in figure 5.8, represents the DC-link output voltage across capacitor of twelve pulse converter which is connected to the three-phase grid. The overall voltage is the addition of outputs obtained from 12 pulse converter. Therefore, 400 volts is connectedwith the CUK converter.

Battery charging results:

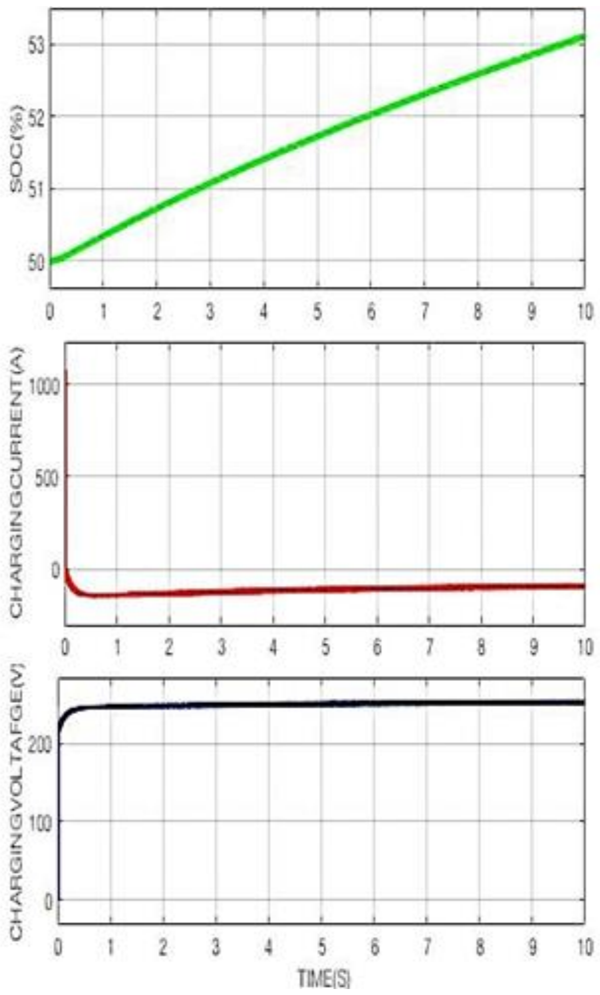


Fig4.9. Simulation result of battery charging during three-phase supply

Simulation results for battery are shown in figure 5.9.

State of charge (SOC) V_S time graph is shown at the top of figure 5.9. It represents the time required by battery for charging from its normal SOC. From the figure, it is observed that the battery charging from 50% to 53% required 10 second.

Charging current(A) V_S time graph is shown in the middle of figure 5.9 This graph represents, the charging current of battery. The negative value of current shows that the battery is drawing current from the supply at constant rate.

Charging voltage V_S time graph is shown at the bottom of figure 5.9. This graph represents, the charging voltage of the battery. Here battery is charging from constant voltage i.e. 230 volts. This voltage also represents the output voltage of CUK converter. Value of voltage depends upon the designed parameters of CUK converter.

Comparing of battery charging rate between three-phase and single-phase:

Battery charging due to single-phase:

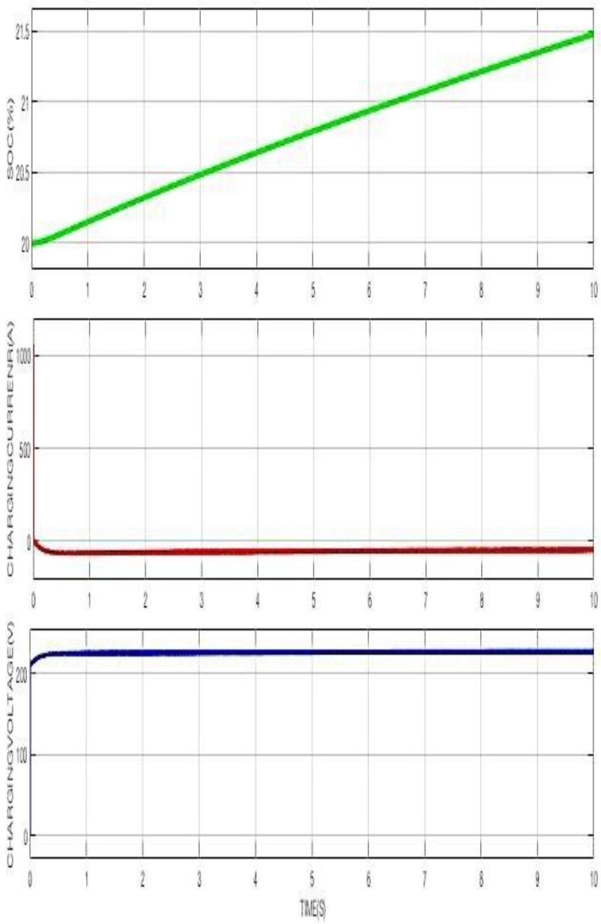


Fig4.10. Simulation result of battery charging for single-phase

Battery charging due to three-phase:

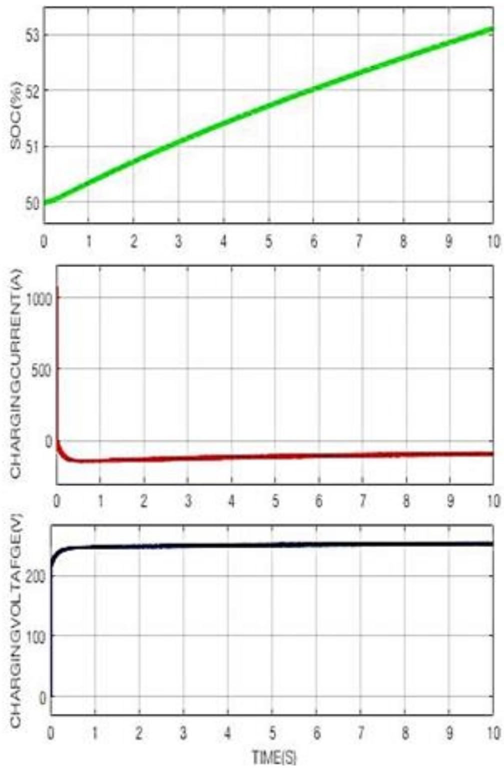


Fig4.11.Simulation result of battery charging for three-phase

Simulation results of battery charging for single phase and three-phase are shown infigure 5.10-5.11.

From the results it is observed that due to single-phase AC source battery is charging from 20% to 21.5% within 10 second whereas due to three-phase AC source battery is charging from 50% to 53% within 10 second. It shows that in three-phase AC source battery charging rate is double compared to single-phase AC source.

Results of discharging the battery:
Variation of I_d and I_q due to controller used in inverter

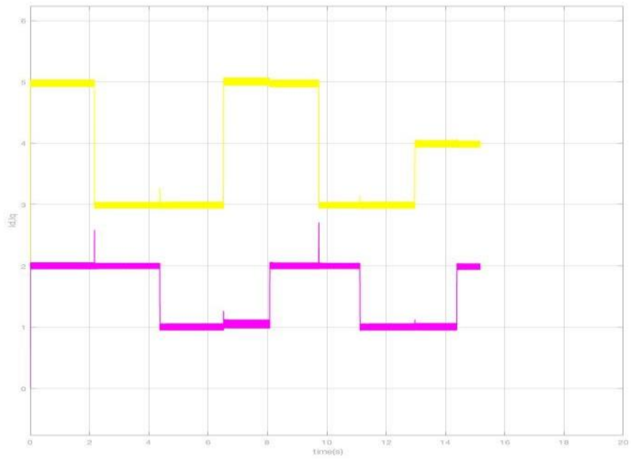


Fig4.12. Simulation results of controller

Simulation results of controller showing variation between I_d and I_q in (A) Vs time in

(s) are shown in figure 5.12. Results shows that by using Clarke's and Park's transformation three-phase RYB is transformed into dq components. The advantage oftaking dq as the reference is that it decoupled both active power and reactive power. Further, results revealed that the variation of I_d doesn't affect the I_q , and variation of I_q doesn't affect I_d. Now, both I_d and I_q are purely decoupled.

Inverter output voltage:

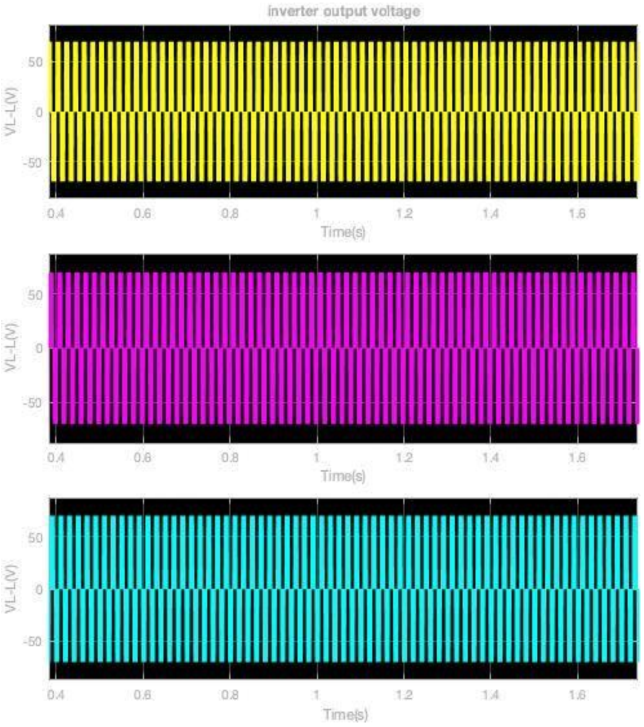


Fig 4.13. Simulation results of line-line voltage output of inverter

Simulation results of line-line voltage output of inverter in volts Vs time in second are shown in figure 5.13. The figure shows the output voltage of two-level inverter and harmonics related to this. Foe an example, three line-line voltage $V_{R\grave{o}}$, $V_{\grave{o}B}$, V_{BR} represented in the graph are having the amplitude of 60 volts. These voltages are not inpure sinusoidal form means they have harmonics.

to grid(V2G) mode or to the induction machine for propulsion mode.

Filtered output voltage from inverter:

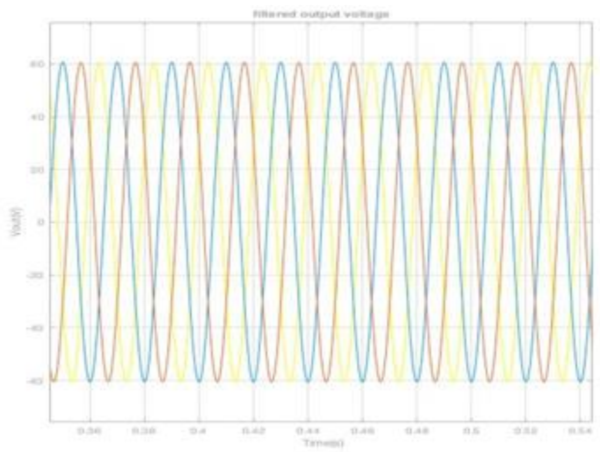


Fig4.14. Simulation result of filtered output line-line voltage of inverter

Simulation results shown in figure 5.14 represents the variation between line-line voltage ($V_{R\grave{o}}$, $V_{\grave{o}B}$, V_{BR}) in volts Vs time in second. From the figure, it is observed that after using inductive filter inverter output is pure sinusoidal. This output can be fed intothe grid in vehicle

Hardware Impelementation

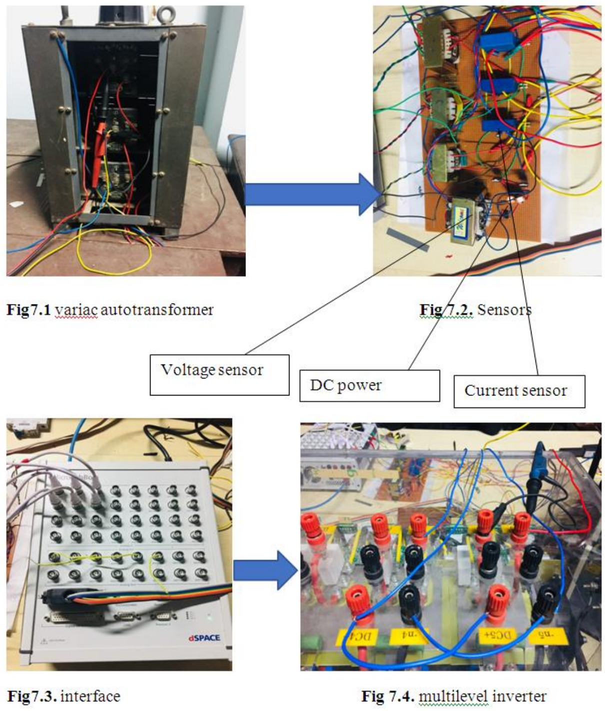


Fig. 4.15 Experimental setup.

This is the hardware implementation, when battery is discharging through inverter and its output is connected through the grid for Vehicle to grid (V2G) mode or output of inverter is fed to the induction machine (IM) for propulsion mode.

Fig6.1 shows, variac autotransformer (230/0-230V) for grid supply and it will be stepped down the voltage to a suitable value.

Fig6.2 shows, the voltage sensor (0-12 V), current sensor (+15V, 0-5V,4-20mA), and power supply to the current sensor (+15V).

Fig6.3 shows, the interface which will interface hardware and software.

Fig6.4 shows, multilevel inverter. Depending upon the level we can use it.Fig6.5 shows, scope meter which will shows the output of inverter.

Voltage sensor: To sense the voltage I chosen transformer of 0-12V rating, which willsense the voltage by autotransformer depend upon the output voltage we require.

Current sensor: To sense the current I chosen current sensor ((+15V, 0-5V,4-20mA),which will sense the current from the grid supply.

Power supply to the current sensor: To operate the current sensor, we require externalDC supply which is taken from external DC source of +15V.

So, Voltage and Current of the grid will be sensed by Voltage and Current sensor andtheir secondary will be given to the interface.

Interface: it will act as analog to digital converter or Digital to Analog converter and it will interface the software and hardware. So, secondary of Voltage sensor and Current sensor is given to the dSPACE interface which will interface the software from the desktop. By software, RYB phase will be converted to $\alpha\beta$ to dq reference for inverter.

Multilevel inverter: DC supply from the battery is given as the input and Pulse width of inverter will be controlled by software. Software input depends upon the grid voltage and current. I my project I needed only two level inverter. So by controlling the pulse width we can change the output of the inverter.

Scope meter: Scope meter will represent the output from the inverter. As it representsthe two level output of inverter.

The output from inverter is further filtered to get pure sinusoidal form to fed to the gridor IM.

V. CONCLUSION

Global warming increasing day by day due to Emission of Greenhouse Gases (GHG) from various sources including public and personal vehicles. Electric Vehicle may play a pivotal role to reduce greenhouse gases. To make Electric Vehicle (EV) customer- friendly, its cost should be at less compared to gasoline-based vehicle, and battery charging should be fast.

In this thesis, simulation is carried out to develop an integrated charger for fast charging of EV. Integrated charger can be plugged in both single-phase and three-phase AC supply. Further, size and cost of EV is reduced by using an integrated charger. Integrated charger contains a DC-DC converter as a CUK converter for both charging and discharging mode due to low switching losses and high efficiency.

Results obtained using BUCK and CUK converter shows that input current fed to the CUK converter has less ripples as compared to the BUCK converter. Integrated charger with CUK converter using both single-phase and three-phase supply has given satisfactory output. Battery charging rate is double in three phase supply compared to single phase supply. Simulation results of the integrated charger with a CUK converter given satisfactory output during controlled discharging Inverter. The proposed integrated charger which is cost effective and fast may be utilized by EV owners in real time for charging their vehicle

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